New Tools and Techniques for Highway Maintenance Management

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Traditional maintenance management systems have been in place in most state highway agencies for more than two decades. These systems have been primarily concerned with the management of maintenance resources such as labor, materials, and equipment. However, because of an environment in highway agency administration that increasingly emphasizes accountability and funding justification, maintenance managers must define the role of maintenance activities in highway facility management. Answers are being sought for questions such as the following: To what extent does a certain level of routine maintenance extend the life of a pavement? How can an optimal level of maintenance be estimated? How can the delivery cost of such activities as winter emergencies be minimized? How can maintenance decisions be made consistent throughout the state? How can one justify a maintenance budget request? The rapid development in technologies makes it possible to provide appropriate answers to some of these questions. Recent advances, for example, in information systems, decision sciences, and computer technology can be utilized to improve productivity and reduce costs in maintenance activities. Such advances are also useful in improving record-keeping practices and in monitoring performance. Some of the new tools and techniques that offer much potential are geographic information systems, fuzzy set mathematics and expert systems, mathematical programming techniques, and computer-aided management systems. These emerging tools and techniques are examined, and their adaptability to state highway routine maintenance management is discussed.

Highway management can be viewed in terms of a three-dimensional matrix (*1*). The first dimension refers to highway facilities, including pavements, bridges, roadside elements, and traffic control devices. The second dimension represents agency objectives such as the provision of acceptable levels of service, preservation of facility conditions, achievement of a decent level of safety, minimization of costs, minimization of negative socioeconomic impacts, conservation of energy, and minimization of environmental degradation. The third dimension refers to agency functions such as planning, design, construction, maintenance, information gathering and management, condition evaluation, and so on.

Over the years, highway agencies have become more and more interested in cutting costs and obtaining best returns. This interest led to the development of a number of management systems, each focusing on a function, facility, objective, or their combinations. Pavement management systems (PMSs) and bridge management systems have been developed to focus on a facility (e.g., pavements or structures), usually addressing capital spending (rehabilitation and construction). Maintenance management systems (MMSs), on the other hand, focus on a function (i.e., maintenance) and have traditionally aimed at improving productivity and work accomplishments.

The existing management systems suffer from two major drawbacks. First, the various systems have evolved almost independent of each other, with little thought given to compatibility and exchange of information. They may have different orientations, not reflecting the impacts of capital spending on maintenance and vice versa. Second, the systems developed during a long period and were designed to run on different computer systems with varying stages of sophistication.

The highway management environment has significantly changed since the first MMSs were developed more than two decades ago. MMSs must adopt new tools and techniques to cope with the changing environment. The new approaches can make use of recent advances in the fields of information systems, decision sciences, and computer technology.

INTEGRATED DATA BASE

Over the years, some management systems were developed for mainframes, some for minis, and some for micros. Hence, incompatibilities among programs exist. Some data base management programs were commercially developed and others were homemade. Consequently, some of the programs used flat files, some used hierarchical files, and some used relational files. Some have fixed record lengths and others have variable length. Worse still, different location referencing systems were used. Noncompatible computer systems even coexisted within one agency in different management systems. Under these conditions, file matching becomes a nightmare, if not impossible. To cut down increasing computer operation costs, many agencies moved from centrally controlled and supported mainframe operations to decentralized, user-supported microcomputer networking systems. Some agencies still maintain a mainframe for central pooling of regional information but use micros for intermediate processing. Existing management systems are not always capable of accommodating the variety of computer environments. In addition, a major hurdle to integration of maintenance information with other management systems has been the lack of a common referencing system.

In the absence of coordination, expensive routine maintenance activities, such as seal coating, are sometimes applied on sections that have been scheduled for resurfacing in a few months. An effective exchange of information between maintenance and major activity programs is thus essential. Figure 1 shows an example of how information on seven major activities can relate to routine maintenance activities.

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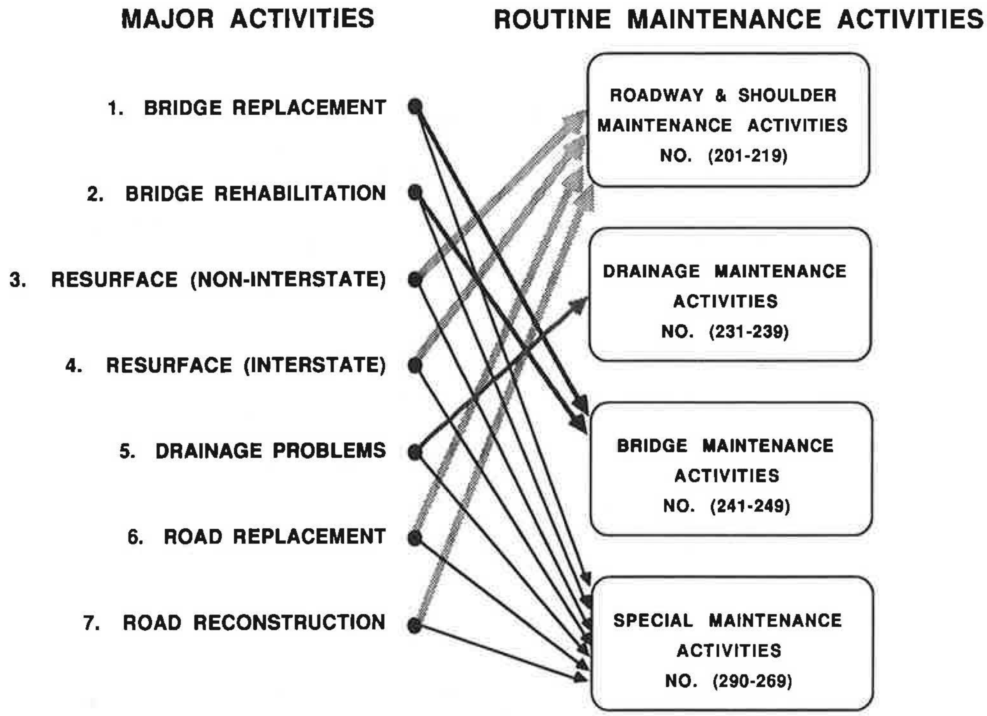


FIGURE 1 Routine maintenance activities as affected by major activities.

Byrd and Sinha (*2*) have discussed data types common to MMSs and PMSs. An example of common data types, involving pavement condition measurements, is given in Figure 2. The data needs of MMSs and other management systems should be carefully examined so that data collection programs can be optimized and individual data bases of different management systems can be integrated for exchange of information as needed.

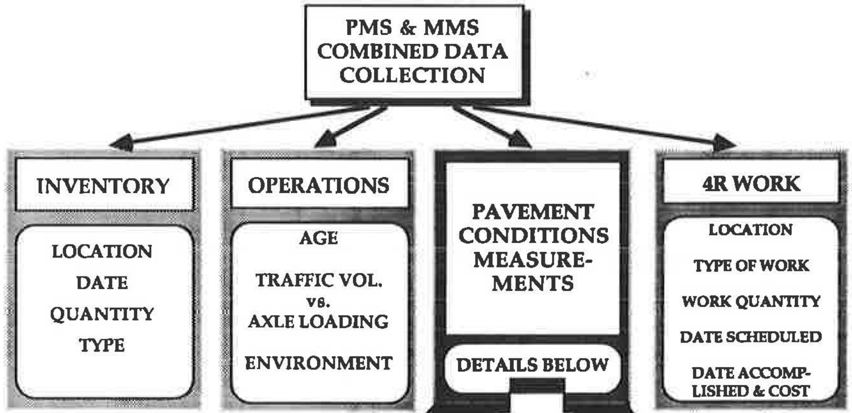
An integrated data base may be sizeable; however, with creativity, data management problems can be overcome. To illustrate, a microcomputer-based routine maintenance data base system was developed for collecting, storing, processing, and retrieving the pavement- and shoulder-related information required in an MMS (*3*). The system can include information on pavement roughness, programmed major activities, traffic, and other data. Because of the largeness of the data file and the relatively slow speed of the personal computer, the indexed sequential technique was used to access information quickly. The information is stored for each of the sections within a subdistrict. To access a specific record in a subdistrict, a search is made in the index file for the subdistrict, and a search for the record is made only in the subfile that includes the records for that specific subdistrict.

The following factors should be considered in developing an integrated data base: type of data to be recorded, frequency of updating, storage and retrieval method, usage of the data by function and line unit, and updating procedures. Special attention should be given to data usage because maintenance information is usually needed at various levels of decision making, such as by top management (for policy purposes) and by the central office (for planning, programming, and budgeting), as well as by the districts, subdistricts, and units (for operations). Standardization will be necessary for the information to be consistent for various uses. For example, "absolute standardization" is required for hierarchical control (through formats) over data storage and retrieval of information, whereas "functional standardization" calls for compatibility of records in allowing the translation of information from one system to another. In all cases, an appropriate common referencing procedure should be used for physical identification of the data.

GEOGRAPHIC INFORMATION SYSTEMS

The need for a common referencing system can be seen from the existence of a critical problem in dealing with maintenance records: the difficulty of identifying the location of maintenance activities undertaken. In many MMSs, maintenance work records are kept by highway section (mostly county line to county line), whereas PMSs use contract sections. Knowing the exact location of both maintenance and capital activities is essential for integrating maintenance with other management systems, if the usefulness of these systems is to be optimized. The rapid development of geographic information systems (GISs) has provided a great opportunity in this area, particularly in combining maintenance information with spatial and other data to produce management information reports.

GISs are simply computerized data base management systems for the storage, retrieval, and display of spatial data (*4*). GISs use two types of data: geocoded spatial data and attribute data. The spatial data are represented by one of two methods, the vector method or the raster method. The vector method represents objects as points, lines, or polygons; the raster method uses the x–y location of the array as an indicator of the spatial location of the point and uses the contents



DATA ITEMS	PMS NTWK	MMS	PMS PROJ	SPECIAL STUDIES OR RES.
SURFACE DISTRESS				
• < Annual		x	x	x
• => Annual	x	x		
ROUGHNESS PROFILE				
• < Annual			x	x
• => Annual	x			
RUTTING/ CROSS SECTIONS				
• < Annual			x	x
• => Annual	x			
SURFACE DISTRESS				
• Random	x			
• Pattern				
• Spot				x
• Continuous		x	x	
SKID RESISTANCE				
• Random	x			
• Pattern				
• Spot				x
• Continuous		x	x	
ROUGHNESS				
• Random	x			
• Pattern				
• Spot				x
• Continuous			x	

DATA ITEMS	PMS NTWK	MMS	PMS PROJ	SPECIAL STUDIES OR RES.
RUTTING				
• Random	x			
• Pattern				
• Spot				x
• Continuous			x	
LOCATION				
• County	x	x	x	
• Route Number	x	x	x	
• Mile Post		x	x	
• Lane		x		
TYPE OF ACTIVITY	x	x	x	
QUANTITY OF WORK	x	x		
COSTS				
• Unit Cost		x		
• Lump Sum		x		
DATE				
• Year	x	x	x	
• Month		x		
• Day		x		
PRODUCTION RATES		x		

FIGURE 2 PMS and MMS combined data collection.

of the array as the attributes of that point. The availability of these two methods gives the GIS two desirable characteristics: flexibility and usefulness. For example, the vector method can present information on road conditions and maintenance performed on a section-by-section basis, whereas the raster representation can be used for preparing and presenting summaries by subdistrict, by district, or for the entire state.

GISs can store and retrieve, analyze, and present data. The ability to store and retrieve data is an advantage because it forces the agency to develop a common referencing system and establish a centralized data base that is accessible by all units. Such a referencing system is required for efficient integration of various files residing with different units of the agency. Traditionally, line units in many agencies viewed a common referencing system as a luxury and never took it seriously. The visual and quick-response enticements of GIS technology improve the likelihood that the subject will be given a higher priority. The staff's ability to respond efficiently to questions from the public or seniors in the agency would be enhanced.

The ability of GISs to analyze data is derived from their ability to link data files to statistical packages, mathematical programs, and plotting software. Consequently, the user can almost instantly extract summary information; statistical results; or graphs about link or system age and condition, classification, priority, scheduled action, and associated key public issues. Summaries of where materials and equipment were used and manpower was tied up can also be extracted from the appropriate files. The user can obtain forecasts about individual sections or the network. For example, the work, materials, and manpower required can all be estimated using mathematical models and displayed graphically or summarized in tables.

The third ability of GISs, presentation of data, allows for preparing quick visual aids for presentation and training and can reduce the work required from drafting staff, such as the preparation of deficiency maps.

Although the benefits are numerous, there are many technical challenges in the development of an effective GIS. Issues that need to be resolved include

- The key questions to answer, or roles the system is to play;
- The referencing system to use;
- The data to include and their structure and design;
- The method to use for portraying information and the information to portray;
- The map scales to use;
- The type of access to allow;
- The type of hardware architecture to use; and
- The protections and securities to put in place.

MAINTENANCE NEEDS ESTIMATION

One of the most important functions of an MMS is to estimate the amount of work to be performed on various highway sections within a maintenance unit during a coming year or season. In most agencies, the budgeting for routine maintenance is established primarily on the basis of historical average quantity standards. Although routine maintenance work loads should be based on road conditions, most current approaches do not provide an assessment of actual needs. A survey procedure was developed for application in Indiana for this purpose (*5*). A condition-based needs assessment and budgeting procedure will provide for a uniformly defined maintenance planning process as well as a tool for checking the maintenance levels of service throughout the network. Such a check is essential for consistency in implementing maintenance policies.

The proposed procedure is to conduct a visual condition survey by unit foremen on a periodic basis. The recommended survey form for asphalt pavements is shown in Figure 3. The approach was tested in the field for validity and accuracy. The surface distresses on highway sections were surveyed by unit foremen. The subjective evaluations of the frequency and severity of distresses were translated to numerical values through a separate analysis. Statistical analyses were then conducted to relate routine maintenance work loads to the subjective evaluation of distresses by unit foremen. For example, it was concluded that the expected work load of shallow patching could be estimated using the following relationship:

DISTRICT ____________ HIGHWAY [SR | US | IS] NO.______

SUBDISTRICT ____________ FROM ____________

UNIT NO. ____________ TO ____________

DATE ____________ TRAFFIC [LOW | MED | HIGH]

DIRECTION [N | S | E | W]

ASPHALT PAVEMENT				
TRAFFIC LANES & PAVED SHOULDERS				
M	S	N	SLIGHT	POTHOLES
M	S	N	MODERATE	
M	S	N	SEVERE	
M	S	N	SLIGHT	CRACKS
M	S	N	MODERATE	
M	S	N	SEVERE	
M	S	N	SLIGHT	RAVELING
M	S	N	MODERATE	
M	S	N	SEVERE	
M	S	N	BLOW UPS, BUMPS AND SURFACE FAILURES	
M	S	N	SLIGHT	RUTTINGS, DIPS
M	S	N	MODERATE	
M	S	N	SEVERE	
M	S	N	SLIGHT	PATCHED SURFACE
M	S	N	MODERATE	
M	S	N	SEVERE	
UNPAVED SHOULDERS				
M	S	N	SLIGHT	BUILD-UP
M	S	N	MODERATE	
M	S	N	SEVERE	
M	S	N	SLIGHT	POTHOLES
M	S	N	MODERATE	
M	S	N	SEVERE	
M	S	N	SLIGHT	DROP-OFF
M	S	N	MODERATE	
M	S	N	SEVERE	
DRAINAGE				
P	F	G	DITCHES	

FIGURE 3 Recommended survey form for asphalt pavements.

$$\text{shallow patching} = 0.157 + 0.09253\,(\text{frequency of potholes}) + 0.10865\,(\text{severity of potholes})$$

where shallow patching is measured in tons per lane mile.

The regression equations were converted into charts, some examples of which are shown in Figure 4. The charts can be used by unit foremen to estimate maintenance work loads once the road conditions have been evaluated. To illustrate, if a road section is found to have "many" "slight" potholes, the amount of shallow patching would be 1.20 tons/lane-mi of the section.

Because the procedure allows the estimation of quantities of needed routine maintenance, it can be applied for budget estimation purposes. It can also be employed, when appropriate, as a tool for periodic scheduling of maintenance work load during the year. The significance of this approach is that it would quantitatively link maintenance to road condition, unlike the current historical averages or arbitrary guess-based methods.

CONDITION AND OTHER DATA ACQUISITION TECHNOLOGIES

Two significant technological developments have enhanced the opportunities for improved management effectiveness: automated data gathering and communications technology. Most states determine maintenance needs by visual observations. Advancements in technology, however, are leading to the introduction of devices that can help quantify more rapidly not only items like roughness and deflections, but also distresses like cracks, potholes, raveling, and so on. Photologging went a long way toward enhancing field condition observation. Still, not all conditions could be detected, and it was necessary to examine the photographs and make judgments on the conditions.

Video, ultrasound, and laser technologies (in which images are identified in binary codes and hence are feasible to store on microcomputers) have provided the ability to integrate three processes: observation, identification, and diagnosis. Enhancements in communications technology and decision support systems now allow for the completion of the decision cycle—that is, the analysis of situations and the actions to undertake.

Maintenance managers can now use technology to observe distress, record the observation, and transmit it to the central processing unit. They can apply accumulated expertise (in the form of expert system models) to determine the appropriate action, the amount of effort and resources required, and an optimal schedule for the deployment of the maintenance crews. All they need to do is ensure that the results make sense and meet their objectives. In cases where special decision rules apply, changes may be required.

Advances in computation and the introduction of interactive hierarchical data base systems have also allowed for linkage of various files maintained by different units in an organization. Such linkage can help bring about better synchronization between capital management and maintenance management.

APPLICATION OF FUZZY SETS MATHEMATICS

Fuzzy sets mathematics can be used in assessing road conditions and in areas employing subjective judgments. The

SHALLOW PATCHING (Tons per Lane Mile)

Assessed Pothole Severity ↓ / Assessed Pothole Frequency →	N	S	M
Sl	0.20	0.50	1.20
Mo	0.60	1.10	2.10
Se	1.20	1.90	3.10

DEEP PATCHING (Tons per Lane Mile)

Assessed Bumps, Blow ups & Surface Failure Frequency ↓ / Assessed Pothole Frequency →	N	S	M
N	0.00	0.04	0.50
S	0.10	0.50	1.30
M	0.90	1.70	3.25

CRACK SEALING (Tons per Lane Mile)

Assessed Severity of Cracks	
Sl	33.23
Mo	103.24
Se	212.73

BLADING SHOULDERS (Shldr Mile per Shldr Mile)

Assessed Frequency of Potholes on Unpaved Shldr	
N	0.10
S	0.30
M	0.90

CLEAN & RESHAPE DITCHES (Ft per Ditch Mile)

Assessed Condition of Roadside Ditch	
P	693.0
F	190.0
G	2.0

FIGURE 4 Proposed present quantity standards.

subjective evaluation of road conditions includes intangible or qualitative information such as wisdom and experience of unit foremen. Fuzzy set theory (*6*), a systematic technique for quantifying imprecise information in the subjective evaluation, can be used to improve the road condition assessment process.

Traditionally, to deal quantitatively with imprecision, the concepts and techniques of probability theory have been employed. Use of probability theory assumes that the imprecision is caused by randomness of variables. However, because the imprecision can be attributed to fuzziness rather than randomness (*6*), the validity of using probability theory to deal with imprecision in decision making is questionable.

Randomness has to do with uncertainty concerning membership or nonmembership of an object in a nonfuzzy set. Fuzziness, on the other hand, has to do with classes in which there may be grades of membership intermediate between full membership and nonmembership. For instance, an ellipse and a square can be drawn side by side. In the concept of randomness of nonfuzzy sets, the answer to the question, Is the shape a circle? is that both shapes are considered "not a circle." However, in the concept of fuzziness, the value of membership belonging to a circle could be 0.0 for a square because a square has no similarity to a circle, and the value of membership for an ellipse could be close to the full membership of 1.0, perhaps 0.90, because an ellipse could well be similar to a circle in shape.

In the road condition evaluation process, a unit foreman must judge the frequency and severity of distresses. For example, the severity of potholes can be slight, moderate, or severe. In a nonfuzzy set approach, the foreman's response can be slight, moderate, or severe. According to the fuzzy sets approach, however, the foreman can quantify a severity level between slight and moderate and between moderate and severe with a numerical rating.

The fuzzy sets approach has been applied in pavement evaluation (*7*), bridge condition rating (*8*), and traffic safety evaluation (*9*). For purposes of illustration, discussion will focus on the use of the approach in rating bridge condition. Bridge condition rating is one of the key indicators in determining the types of repair or maintenance required for a bridge. The usefulness of a bridge maintenance program, therefore, depends on the reliability and accuracy of bridge inspection information. Current bridge inspection practices, however, suffer from three inherent shortcomings (*8*):

1. The parameters in bridge inspections are not completely defined or cannot be precisely measured,
2. Bias and subjectiveness are often included but not systematically accounted for in the evaluation process, and
3. Guidelines for establishing the relationship between the extent of deterioration and the assignment of values of condition rating are lacking.

The purpose of the condition assessment model used as an illustrative example in this paper was to filter the field inspection data of inconsistencies before entering the bridge management system. It was concluded that fuzzy set theory (*6*) was effective in minimizing the bias in judgment and enhancing the overall accuracy of the bridge condition evaluation. One method for combining fuzzy knowledge, the fuzzy weighted average (*10*), was used in the model. The fuzzy weighted average has a simple mathematical form:

$$R = \frac{1}{\sum W_i} * \sum (W_i * r_i) \tag{1}$$

where

R = a fuzzy number denoting a bridge component's resultant rating,
r_i = the fuzzy rating of the ith subcomponent, and
W_i = the fuzzy importance factor for the ith subcomponent.

The importance factors are generally imprecise quantities and are represented as fuzzy sets. In this model, three bridge components (deck, superstructure, and substructure) were further divided into subcomponents, as shown in Figure 5. Equation 1 represents the fuzzy relationship between the condition of a bridge component and those of its subcomponents. W_i represents the degree of importance of a subcomponent relative to other subcomponents. A detailed discussion of this model and the method of determining fuzzy importance factors can be found elsewhere (*8*).

A microcomputer-based software package for the condition assessment model was developed. The results were in good agreement with the assessment of experienced bridge inspectors. Consequently, the package can be used as an expert system for bridge inspection, particularly for assisting new and inexperienced bridge inspectors.

USE OF EXPERT SYSTEMS

An expert system is defined as a problem-solving computer program for dealing with difficult problems demanding specialized knowledge and skill. It solves real-world, complex

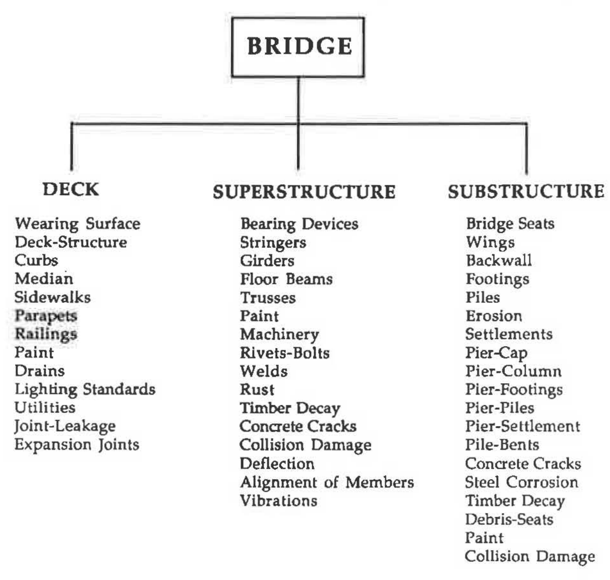


FIGURE 5 Division of bridge components into subcomponents.

problems requiring expert interpretation by using a computer model of expert reasoning. Conclusions are the same as those a human expert would reach if faced with the same problem (*11*). Expert systems are useful when real experts are not available. In addition, expert systems are useful for documenting expert knowledge in a way that is not feasible in books or manuals.

Why are expert systems important? There is a considerable turnover in the ranks of maintenance management; in addition, many experienced personnel are now retiring. Yet many maintenance decisions are made by unit foremen and subdistrict superintendents or field supervisors on the basis of their judgment. If they do not have ample experience, expert systems can help fill the gap. To illustrate, maintenance needs estimation through visual inspection requires foremen not only to correctly assess the road condition, but also to convert the road condition information into work loads. Although the foreman can be trained to assess the road condition, work load estimation demands considerable experience and know-how. There is inherent uncertainty in the unit foreman's translation of distress information into the type and amount of activities to be performed. A knowledge-based expert system could be applied to take care of the uncertainty in the estimation process. It provides a tool for estimating the activities in the absence of an expert. The knowledge base can be tested and altered over time to improve its performance. Because the computer stores the expert system, it can become a part of a larger cost estimation system for the entire road network.

There are several examples of expert systems developed for highway maintenance and rehabilitation management (*12–14*). A discussion of one is presented below.

An expert system was developed for estimating the maintenance work load on asphalt roads and shoulders in the Indiana state highway system (*13*). The maintenance activities related to roadway and shoulder included shallow patching, deep patching, crack sealing, full-width shoulder sealing, seal coating, and leveling. Five types of distresses were considered: potholes; cracks; raveling; blowups, bumps, and surface failures; and rutting and dips.

The collective expertise of 18 randomly selected unit foremen was used for knowledge acquisition. The computer program was written in LISP. There are several advantages of using LISP instead of other languages. The most significant is the flexibility LISP allows for manipulating the knowledge base, which may require change as new information is obtained.

The program is to be used interactively by unit foremen to estimate maintenance work loads on the basis of field observations of pavement and shoulder distresses. The program requires the user to answer questions about the physical characteristics of the highway section, including distress information. The flowchart for the overall program is shown in Figure 6.

The input module fetches all the information from the user. The knowledge base stores all the rules. This is where the expert system applies its own knowledge to the facts provided by the user to develop the conclusions. It has two distinct subdivisions. The first, the conversion module, contains the rules for qualitative values of distresses to be converted into quantitative values through a series of IF-THEN statements. The second part, the rules module, which can also be called the inference engine, includes the rules to estimate the amount

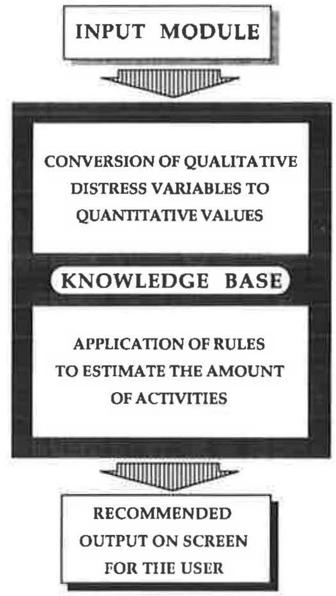


FIGURE 6 Flowchart for expert system.

of activities and their costs. The output module controls the execution of the entire program and provides outputs in desired formats.

An example of the input and output information for a 10-mi highway section is given in Figure 7. The work load and costs are expressed as 95 percent confidence ranges.

One of the major causes for the large variation in the estimated work loads is the choice of different activities by foremen for the same type of distress. Some types of distress can trigger different activities, and an activity can correct more than one type of distress. Furthermore, different practices may be expected in different parts of the state. The reasons might be unavailability of materials for a particular activity, one activity being less expensive due to proximity of the site to a mixing plant, and so on. More research is needed so that information about regional practices can be included in the input module before the estimation process.

OPTIMAL PROGRAMMING AND SCHEDULING

Timing, frequency, extent, and type of routine maintenance work have a significant impact on the performance of highway pavements and other elements (*15,16*). An important function of an MMS is therefore to provide maintenance managers with an effective tool for formulating a "good" routine maintenance program one that maintains and preserves the road network under their charge at or above a desired standard.

Unfortunately, many factors make the task of developing a good routine maintenance program difficult:

- Highway maintenance units often have to perform diverse routine maintenance activities on many highway routes over extended areas; these activities have possible consequences of different importance.
- The highways in question may vary from a six-lane Interstate highway to a lightly traveled two-lane road.

INPUT

ROAD SECTION LENGTH (in miles)	: 10
NUMBER OF LANES-- ONE WAY ONLY	: 1
LANE WIDTH (in feet)	: 11.5
INSIDE SHOULDER WIDTH (in feet)	: 3
OUTSIDE SHOULDER WIDTH (in feet)	: 6

CRACKS	SEVERITY	: moderate
	FREQUENCY	: many
POTHOLES	SEVERITY	: slight
	FREQUENCY	: few
RAVELING	SEVERITY	: slight
	FREQUENCY	: none
BLOW UPS, BUMPS AND SURFACE FAILURES		
	FREQUENCY	: many
RUTTING & DIPS	SEVERITY	: severe
	FREQUENCY	: many

OUTPUT

AMOUNT OF WORK

SHALLOW PATCHING	5.2 - 6.1 tons
CRACK SEALING	1359 - 1584 gallons
FULL WIDTH SHOULDER SEALING	0 - 7 ft-miles
SEAL COATING	0 - 1.7 lane-miles
DEEP PATCHING	8.6 - 9.8 tons
LEVELING	161 - 162 tons

ESTIMATED COSTS

SHALLOW PATCHING	$ 598 - 701
CRACK SEALING	$ 2,827 - 3,294
FULL WIDTH SHOULDER SEALING	$ 0 - 832
SEAL COATING	$ 0 - 2,858
DEEP PATCHING	$ 575 - 655
LEVELING	$ 7,411 - 7,477

FIGURE 7 Example of maintenance work load and cost estimation by expert system.

- Because of resource constraints, not all maintenance needs can be attended to as and when required.
- A routine maintenance program must be planned in coordination with the highway rehabilitation program to obtain the maximum return.

Given this complexity, the most appropriate technique for this situation appears to be optimization. Optimization models are most useful because they define the ideal work mix under a set of prevailing constraints. For example, an integer programming approach was found to provide a good tool for application at the unit, subdistrict, district, or even at the statewide level in Indiana (*17*). The objective function of the model attempts to maximize the preservation of the condition of various highway elements by maximizing the sum of equivalent workday units of routine maintenance activities, each weighted by an appropriate priority factor. The constraints considered include maintenance need requirements; the budget available for the maintenance unit; manpower, material, and equipment availability; and the rehabilitation of the highway sections. The assignment of priority weighting factors considers (*a*) the relative importance of each routine maintenance activity in preserving the highway system at a desired level of service condition, (*b*) the urgency of need for maintenance work in relation to the severity of distress, and (*c*) the type of highway section or highway class.

Such an optimization model can allow for the analysis of shortfalls and surpluses of resources. The benefits of reallocating resources can be examined by performing parameter sensitivity analyses. These analyses are useful because certain parameters might have been a result of managerial policy decisions, and such decisions can be revised after their consequences in terms of what could otherwise be achieved are revealed. The amount of certain resources to be apportioned to a given activity may need adjustment to achieve better results. For instance, the number of temporary laborers to be hired during a given period could be determined by such analyses.

The proposed optimization approach has great potential to enhance the efficiency and effectiveness of MMSs. However, extensive data are needed for successful application of the optimization model. All these data should be readily available in a fully operational MMS. The value and usefulness of the output information depend on the accuracy and exhaustiveness of the acquired data as well as on the skills of the user in interpreting the results obtained from the model. The establishment of an appropriate routine maintenance data base and a good understanding of the operation are prerequisites for a meaningful routine maintenance programming analysis.

Another example of the application of the optimization approach is a model that was developed for use in the reassignment of summer personnel to alternative site locations for winter snow and ice control activities (*18*). The model was developed for application at the district level in Indiana. The model is an integer program that can generate trade-off curves between the objectives of minimizing the total distance that the reassigned workers must travel from their respective homes to one of many site locations and minimizing the maximum distance that any worker must travel. System constraints include demand requirements for workers at each site and the limited availability of state-owned vehicles that may be issued to workers assigned to remote sites. The results indicated that the use of the model could save one district alone about $100,000 during the 1984–1985 snow season.

CONCLUDING REMARKS

With the shift of emphasis from system development to system preservation and maintenance, challenges that demand innovation and creativity face the maintenance managers of state highway agencies. Traditional MMSs, developed more than two decades ago and designed primarily to monitor and control maintenance resources, cannot deal with the changing requirements of maintenance management. Maintenance managers increasingly are being asked to answer questions such as, To what extent does a certain level of routine maintenance extend the life of a pavement? How can an optimal level of maintenance be estimated? How can the cost of such activities as winter emergencies be minimized? How can maintenance decisions be made consistent throughout the state? How can a maintenance budget request be justified? The rapid development in technologies makes it possible to provide appropriate answers to some of these questions. Recent advances in information systems, decision sciences, and computer technology can improve productivity and reduce the cost of maintenance activities. A brief review of some of the emerging tools and techniques that can be used by highway maintenance managers has been presented. These include fuzzy sets mathematics, expert systems, optimization techniques, GISs, and other computer software and hardware technologies.

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